SIMULATED WAVE WATER SCULPTURE

BACKGROUND OF THE INVENTION

1. Field of the Invention The present invention relates in general to the formation of water sculptures, and, more particularly, to a method and apparatus for providing a flowing body of water on an inclined surface to produce simulated wave shapes for aesthetic purposes such as for water fountains, water sculptures and the like.

2. Description of the Related Art

The concept of using water to create shapes of aesthetic beauty can broadly be categorized in the field of water sculpture. Examples of water sculpture can be seen in water fountains, water geysers and man-made or simulated rivers and waterfalls. These types of sculptures demonstrate numerous possibilities for creating different aesthetic water shapes. For instance, in the case of a man-made river, water can be shaped by being directed over and around various obstacles such as rocks. Water can also be made to fall from heights, as in waterfalls and fountains. Certain fountains may employ streams of water projecting upward or outward at different velocities, angles and volumes to create unique and appealing shapes, configurations or patterns.

Despite the many approaches to forming water sculptures, there have been relatively few attempts to create realistic-looking wave-like shapes or wave-forms. Of the several attempts that have been made, most have focused on natural propagating waves, i.e., waves that simulate conditions naturally found on beaches and elsewhere in the environment. Natural propagating wave simulation, however, is not ideal for the formation of water sculptures due to the need for a deep water source. Because water sculptures typically must operate in a limited amount of space using only limited amounts of water, deep water wave propagation would be inappropriate for many such sculptures. Further, the use of deep water creates problems of cost, size and capacity. Specifically, the reproduction of natural propagating waves in deep water requires expensive water containment and wave generating equipment.

SUMMARY OF THE INVENTION

The present invention overcomes many of the limitations of the prior art by providing a method and apparatus for producing natural-looking waves under shallow water conditions. In particular, a water sculpture is provided that can produce several types of wave forms occurring in a natural deep-water environment, but without the costs or space requirements associated with deep water wave propagation. Examples of such natural wave forms include: (1) undulating, unbroken waves; (2) breaking waves forming a white water bore; (3) curling or spilling waves; and (4) tube or tunnel waves.

The invention generally involves the use of a flow surface over which a relatively shallow flow or "sheet flow" of water is injected by a nozzle or other suitable means. The term sheet flow is a convenient term to describe water flow that follows the general contours of a flow surface. It should not be construed as limiting in any way the scope or application of the present invention. The flow surface is generally inclined, but in other respects may have a contour that is widely varied. It may also be tilted or declined if desired. For instance, the surface may be symmetrical, asymmetrical, planar, convex, concave, canted about its longitudinal axis, and/or provided with mounds, shapes, forms, or other contours in order to produce a wave of a particular shape or aesthetic appeal. Advantageously, by providing a flow of water over an appropriately formed surface, wave-like shapes simulating an unbroken wave face, a white water bore, a spilling breaking wave, a breaking tunnel wave or other desired wave shapes can be created.

In accordance with one embodiment the present invention provides a water sculpture comprising a flow surface with at least a portion thereof having a generally inclined slope. A source of water is provided for injecting a sheet flow of water onto the flow surface such that the sheet flow of water flows upwardly onto the inclined slope and substantially conforms to the contours thereof. The flow surface is formed such that it causes at least a portion of the sheet flow of water to separate from the flow surface producing a simulated wave form.

In accordance with another embodiment the present invention provides an apparatus for forming a water sculpture, comprising a flow surface with at least a portion thereof having a generally inclined slope. A flow source is provided injecting a shallow flow of water onto the flow surface such that the shallow flow of water flows upwardly onto the inclined slope and substantially conforms to the contours thereof. The flow surface further comprises an upwardly rising section sized and configured so as to induce separation of the shallow flow of water on said upwardly rising section, whereby at least a portion of the water flow assumes an airborne trajectory producing visual, aural and/or aesthetic appeal.

In accordance with another embodiment the present invention provides a water awning for a building or the like comprising a tunnel wave water sculpture forming a sheet flow of water which assumes a trajectory over a walkway or entranceway.

In accordance with another embodiment the present invention provides a walkthrough water sculpture comprising a platform or walkway for allowing pedestrians or vehicles to traverse a predetermined distance and a flow surface disposed adjacent to the walkway and having a generally inclined slope. A flow source is provided for injecting a sheet flow of water onto the flow surface such that the sheet flow of water flows upwardly onto the inclined slope and substantially conforms to the contours thereof. The flow surface further comprises an upwardly rising section sized and configured so as to induce separation of the sheet flow on the upwardly rising section, whereby at least a portion of the sheet flow of water assumes an airborne trajectory over the walkway.

In accordance with another embodiment the present invention provides a water sculpture, comprising a contoured inclined flow surface and one or more flow sources for providing a flow of water onto the inclined flow surface, such that the flow substantially conforms to the contours of the flow surface. The flow surface further comprises an upwardly rising section sized and configured so as to induce separation of the flow of water on the upwardly rising section, whereby at least a portion of the flow of water assumes a path or trajectory that simulates a naturally occurring wave form.

These and other features and advantages of the present invention will be readily apparent to those skilled in the art having reference to the drawings and detailed description that follows, the invention not being limited to any particular preferred embodiment(s) described.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B are perspective views of two types of sheet flow water sculptures having features in accordance with the present invention;

FIG. 2 is a schematic perspective view of the sheet flow water sculpture of FIG. 1A, illustrating a supercritical sheet flow of water thereon;

FIG. 3 is a perspective view of the sheet flow water sculpture of FIG. 1A, illustrating a critical sheet flow of water thereon forming a white water bore;

FIG. 4A is a perspective view of the sheet flow water sculpture of FIG. 1A, illustrating a spilling wave formed by a cross-stream velocity gradient;

FIG. 4B is a perspective view of a modified sheet flow water sculpture, illustrating a spilling wave formed by a cross-stream pressure gradient;

FIG. 5 is a front elevational cross-section view of a tunnel wave water sculpture having features in accordance with the present invention;

FIG. 6A is a perspective view of an alternative embodiment of a tunnel wave water sculpture having features in accordance with the present invention;

FIG. 6B is a topographical plan view of the tunnel wave water sculpture of FIG. 6A;

FIG. 6C is a schematic plan view of the tunnel wave water sculpture of FIGS. 6A and 6B illustrating streamline trajectories of water flow upon the flow surface;

FIGS. 7A, 7B and 7C are schematic perspective views of the tunnel wave water sculpture of FIGS. 6A–C, illustrating three possible modes of operation;

FIG. 8 is a perspective view of a half-pipe water sculpture having features in accordance with the present invention;

FIG. 9 is a schematic perspective view of an alternative embodiment of a half-pipe water sculpture having features in accordance with the present invention;

FIG. 10A is a perspective view of a tunnel wave awning water sculpture having features in accordance with the present invention;

FIG. 10B is a front elevational cross-section view of the tunnel wave awning water sculpture of FIG. 10A;

FIG. 10C is a schematic plan view of the tunnel wave awning water sculpture of FIGS. 10A–B, illustrating streamline trajectories of water flow upon the flow surface;

FIGS. 11A and 11B are perspective and front elevational cross-section views, respectively, of an alternative embodiment of a tunnel wave awning water sculpture having features in accordance with the present invention;

FIGS. 12A and 12B are perspective and front elevational cross-section views, respectively, of a second alternative embodiment of a tunnel wave awning water sculpture having features in accordance with the present invention; and

FIGS. 13A–C are time-sequenced perspective views of a dynamic water sculpture having features in accordance with present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

My U.S. Pat. No. 5,236,280 first disclosed the concept of simulated surfing wave forms in a shallow or "sheet flow" water environment. One purpose of creating these wave shapes was to reproduce desired conditions in which surfers and other ride participants could wave-ride on simulated waves and thereby perform exciting new water-skimming maneuvers over a sustained period of time. My U.S. Pat. No. 5,401,117 further expanded this concept by providing a method and apparatus for containerless sheet flow which produced improved wave shapes for performing surfing maneuvers.

The present invention further improves and expands on this fundamental concept of producing simulated wave shapes by forming new and unique water sculptures having visual, aural and/or aesthetic appeal. This adaptation leads to some unique applications, such as an awning for an entranceway to a building, or an indoor breaking wave water sculpture to complement a surfing or beach theme. The overall result is the creation of a wide variety of desirable wave-shapes that can be used generally in water fountains and other applications intended for visual, aural or aesthetic appeal.

Definitions

To better understand the preferred construction and operation of the invention as described herein, a few special terms are defined below. However, it should be pointed out that these explanations are intended to supplement the ordinary meaning of such terms, and are not intended to be limiting in any way.

A stationary wave is a progressive wave that is travelling against the flow of water and has a phase speed that exactly matches the speed of the current, thus, allowing the wave to appear stationary.

The equilibrium zone is that portion of an upward inclined flow surface upon which an actual or hypothetical object may be maintained in equilibrium on an upward flowing body of water. Consequently, the upslope flow of momentum as communicated to the object through hydrodynamic drag is balanced by the downslope component of gravity associated with the weight of the object.

The supra-equidyne area is that portion of a flow surface contiguous with but downstream of the equilibrium zone wherein the slope of the incline is sufficiently steep to allow an object to overcome the drag force associated with the upwardly sheeting water flow and slide downwardly thereupon.

The sub-equidyne area is that portion of a flow surface contiguous with but upstream of the equilibrium zone wherein the slope of the incline is either insufficiently steep, flat or declined such that the drag force associated with the water flow causes an object to move in the direction of flow and ultimately back up the incline in opposition to the downslope component of gravity.

Of course, those persons skilled in the art will recognize that the terms equilibrium, supra-equidyne and sub-equidyne, as used herein, are relative terms and may vary depending upon the size, shape, weight and drag coefficient of the actual or hypothetical object placed in the flowing body of water. Nevertheless, they are useful and convenient terms for describing the general characteristics of various flow supporting surfaces as disclosed herein.

The Froude number is a mathematical expression that describes the ratio of the velocity of the flow to the phase speed of the longest possible waves that can exist in a given depth without being destroyed by breaking. The Froude number equals the flow velocity divided by the square root of the product of the acceleration of gravity and the depth of the water. The Froude number squared is a ratio between the kinetic energy of the flow and its potential energy, i.e., the Froude number squared equals the flow speed squared divided by the product of the acceleration of gravity and the water depth. In formula notation, the Froude number may be represented by the following mathematical expression:

$$F = \frac{v}{\sqrt{gd}}$$

where:

v=flow velocity in ft/sec

g=acceleration due to gravity in ft/sec^2

d=depth of the sheet water flow in ft.

Critical flow occurs when the flow's kinetic energy and gravitational potential energy are equal. Critical flow has the characteristic physical feature of a breaking phenomenon or a hydraulic jump resulting from a local convergence of energy. Because of the unstable nature of wave breaking, critical flow is difficult to maintain in an absolutely stationary state in a moving stream of water given that the speed of the wave must match the velocity of the stream to remain stationary. This is a delicate balancing act. There is a match for these exact conditions at only one point for one particular flow speed and depth. Critical flows have a Froude number equal to one.

Subcritical flow can be generally described as a slower moving water flow. Specifically, subcritical flows have a Froude number that is less than 1, and the kinetic energy of the flow is less than its gravitational potential energy. If a stationary wave is in subcritical flow, then it will be a non-breaking stationary wave.

Supercritical flow can be generally described as faster moving water flow. Specifically, supercritical flows have a Froude number greater than 1, and, thus, the kinetic energy of the flow is greater than its gravitational potential energy. No stationary waves are involved. The reason for the lack of stationary waves is that neither breaking nor non-breaking waves can keep up with the flow speed because the maximum possible speed for any wave is the square root of the product of the acceleration of gravity times the water depth. Consequently, any waves which might form are quickly swept downstream.

The hydraulic jump is the point of wave-breaking of the fastest waves that can exist at a given depth of water. The hydraulic jump itself is actually the break point of that wave, resulting from a local convergence of energy. Any waves occurring upstream of the hydraulic jump in the supercritical area are unable to keep up with the flow. Consequently they bleed downstream until they meet the area where the hydraulic jump occurs. At that point, the flow is thicker and the waves can travel faster. Concurrently, the downstream waves that can travel faster move upstream and meet at the hydraulic jump. The convergence of waves at this flux point leads to wave breaking. In terms of energy, the hydraulic jump is an energy transition point where energy of the flow abruptly changes from kinetic to potential. A hydraulic jump occurs when the Froude number is 1.

White water breaking occurs due to wave breaking at the leading edge of the hydraulic jump where the flow transitions from critical to subcritical. In the sheet flow environment, remnant turbulence and air bubbles from wave breaking are merely swept downstream through the subcritical area, and dissipate within a short distance downstream of the hydraulic jump.

A bore is a progressive hydraulic jump which can appear stationary in a current when the bore speed is equal and opposite to the current.

Separation is the point where the sheet flow breaks away from the flow surface. Flow separation results from differential losses of kinetic energy through the depth of the sheet flow. As the sheet flow proceeds up the incline it begins to decelerate, trading kinetic energy for gravitational potential energy. The portion of the sheet flow that is directly adjacent to the walls of the incline (the boundary layer) also suffers additional kinetic energy loss to wall friction. These additional friction losses cause the boundary layer to run out of kinetic energy and come to rest in a state of zero wall friction while the outer portion of the sheet flow still has residual kinetic energy left. At this point the outer portion of the sheet flow breaks away from the wall of the incline (separation) and continues on a ballistic trajectory with its remaining energy forming either a spill down or curl over back upon the upcoming flow. The separating streamline is the path taken by the outer portion of the sheet flow which does not come to rest under the influence of frictional effects, but breaks away from the wall surface at the point of separation.

Flow partitioning is the lateral division of flows having different hydraulic states. A dividing streamline is the streamline defining the position of flow partitioning on the surface along which flows divide laterally between supercritical and critical hydraulic states.

Conforming flow occurs where the angle of incidence of the entire depth range of a body of water is (at a particular point relative to the inclined flow forming surface over which it flows) predominantly tangential to the flow surface. Consequently, conforming flow upon a flow surface will conform to gradual changes in inclination, e.g., curves, without causing the flow to separate. As a consequence of flow conformity, the downstream termination of an inclined surface will always physically direct and point a conforming flow in a direction aligned with the downstream termination surface. The change in direction of a conforming flow can exceed 180 degrees in some cases.

The following detailed disclosure and drawings set forth several particularly preferred embodiments of certain water sculptures having features and advantages in accordance with the preset invention. For convenience throughout the various examples, like numbers are used to refer to like elements. However, the use of the same or similar numbers in different figures should not in any way be interpreted as requiring identity of structure or function. Also, while water is the preferred flow medium those skilled in the art will readily appreciate that a wide variety of other suitable liquids may also be used, including without limitation colored liquids, liquid mixtures, and various beverages, such as champagne and the like.

Example 1

Basic Sheet Flow

FIG. 1A shows one embodiment of a simple water sculpture **10*a*** having features of the present invention. Sectional lines as revealed in FIG. 1A are solely for the purpose of indicating the three-dimensional shape in general, and are not illustrative of a specific frame, plan, or profile sections. Rather, it should be noted that a wide variety of dimensions and configurations for the water sculpture **10*a*** are compatible with the principles and teachings of the present invention. Therefore, these principles and teachings should not be construed to be limited to any particular configuration illustrated in the drawings or described herein.

The water sculpture **10*a*** generally comprises a sub-surface structural support **12** and a flow surface **14*a***, defined by upstream edge **16**, downstream edge **18**, and side edges **20*a*** and **20*b***. The flow surface **14*a*** is preferably smooth and can be a skin placed over the sub-surface structural support **12**, or the structures can be integrated together, provided that the flow surface is sufficiently smooth. The flow surface **14*a*** can be fabricated of any of several well known materials, e.g., plastic; foam; formed metal; stretched or reinforced tension fabric; treated wood; fiberglass; tile; fluid filled plastic or fabric bladders; or any other suitable materials having a sufficiently smooth outer surface and which will withstand the surface loads involved. Sub-surface structural support **12** can be sand/gravel/rock; truss and beam; thin shell concrete; compacted fill; tension pole; or any other suitable materials for firmly grounding and structurally

supporting the flow surface **14***a* in a manner so as to receive flowing water thereon.

FIG. **1B** shows an alternate embodiment of a water sculpture **10***b* having features in accordance with the present invention. In this case, the flow surface **14***b* has a generally concave curvature transitioning into a convex curvature defining a ridge line **18**, as shown. Shaping of the flow surface **14***b* helps to determine the shape of the water flowing on the surface, as the water generally closely conforms to the contours of the flow surface **14***b* due to the nature of shallow water flow. Of course, many other shapes and configurations of the flow surface **14***b* may also be used such as a variety of straight, concave and convex curvatures, as will be explained below.

FIG. **2** is a schematic diagram illustrating sheet flow on the flow surface **14***a* of FIG. **1A**. The flow surface **14***a* is generally inclined upwards. A flow source **22** (e.g., pump, fast moving stream or elevated dam/reservoir or nozzle) forms a supercritical flow of water **24** in a predominantly singular flow direction **26** (as indicated by arrows) over flow surface **14***a* to form an inclined flowing body of water. There is no minimum or maximum depth for supercritical flow **24**, although shallow flows are preferred, with a practical minimum of approximately ½ cm. The depth of water will range preferably from about ½ to 40 centimeters. The preferred relation of flow depth to flow speed can be expressed in terms of a preferred Froude number. A practical regime of Froude numbers for water flow over surface **14***a* is from about 2 to about 75, with the preferred range being between about 4 and 25. Flows with Froude numbers less than 2 are prone to contamination from pulsating motions known as "roll waves" which are actually vortices rather than waves.

The flow surface **14***a* as shown and described in connection with FIGS. **1** and **2** can be used to simulate a variety of wave forms, such as a stationary, unbroken wave. Maintenance of this "unbroken" wave requires that the kinetic energy of supercritical flow **24** always exceed the potential energy downstream of the edge or ridge line **18**.

Example 2

Simulated White Water Bore

FIG. **3** illustrates a water sculpture **10** with a flow profile that simulates a stationary white water bore. When the velocity (i.e., kinetic energy) of an upwardly inclined supercritical sheet flow **24**, moving in direction **26**, is less than the gravitational potential energy downstream of the upper edge or ridge line **18**, then sheet flow **24** will form a hydraulic jump **28** prior to reaching downstream ridge line **18**. Accordingly, white water **30** will roll downward and to the side as run-off water **32**, and, an effect similar to a stationary white water bore will form on the flow surface **14***a*. Maintenance of this hydraulic state requires that the kinetic energy of supercritical flow **24** always be less than the potential energy at the downstream edge or ridge line **18**. The relative position of the hydraulic jump **28** will be determined by the velocity of the supercritical flow **24**. The higher the velocity, the higher the position of the hydraulic jump **28** upon flow surface **14***a*.

Example 3

Simulated Spilling Wave

A simulated spilling wave with a smooth unbroken shoulder may be created on a flow surface by two general methods: (1) a cross-stream velocity gradient and (2) a cross-stream pressure gradient. The use of either method depends upon overall objectives and constraints of the flow surface structure and available flow characteristics. A cross-stream velocity gradient is the preferred method when the structure of the flow surface is limited to a symmetrical configuration such as flow surface **14***a* shown in FIG. **4A**. A cross-stream pressure gradient is the preferred method when the initial supercritical flow **24** moving up the flow surface has constant velocity such as shown in FIG. **4B**.

FIG. **4A** depicts one preferred method for producing a simulated spilling wave with a smooth unbroken shoulder. This wave is created by introducing a cross-stream velocity gradient to a supercritical flow of water that moves in direction **26** up the flow surface **14***a* with a level ridge line **18**. The "spilling breaker" effect results from the initial supercritical flow **24***a* and **24***b* issuing from respective flow sources **22***a* and **22***b* at two distinct velocities and manifesting two subsequent coexisting hydraulic states, i.e., a higher velocity supercritical flow **24***a* over the top of ridge line **18** (associated with flow source **22***a*) and an adjacent lower velocity supercritical flow **24***b* (associated with flow source **22***b*). The white water **30** that results from this cross-stream velocity gradient is formed by a hydraulic jump **28** located below the ridge line **18**. Flow surface **14***a* allows spilling white water **30** to ventilate off the side **20** of the flow surface **14**a as run-off water **32**, thus avoiding supercritical flow submersion.

The cross-stream velocity gradients as described above were created by placing multiple flow sources of differing kinetic energy side by side and simultaneously projecting them upslope as shown in FIG. **4A**. An alternative way of creating cross-stream velocity gradients employs the use of a single source of water with a specially configured nozzle or plenum. For instance, nozzles with asymmetrical apertures can be used to produce the same effect.

As noted above, a second general approach to simulating a spilling wave with a smooth unbroken shoulder is to generate a cross-stream pressure gradient. Such cross-stream pressure gradients can be generated, for example, by sills, depressions, injected water, etc. The preferred technique, in order to avoid penetrations or discontinuity on flow surface **14***c*, is through increased hydrostatic pressure. In this regard, FIG. **4B** shows a water sculpture **10***c* having a flow surface **14***c* that is asymmetrically extended (as indicated by dashed lines) to form a downstream ridge line **18** of increasing elevation. Thus, with a proper angle and length of flow surface **14***c* two subsequent coexisting hydraulic states will result, i.e., the supercritical flow **24***a* that flows over shortened side **18***a* of downstream ridge line **18** will clear and sustain its supercritical character, while flow **24***b* has insufficient kinetic energy to clear extended side **18***b* of downstream ridge line **18** and will subsequently suffer a hydraulic jump **28** and exhibit white water **30** at a lower elevation on flow surface **14***c* of water sculpture **10***c*. The same effect can be achieved and/or enhanced by causing the extended side **18***b* to be sloped at a greater angle of inclination than the flow surface **14***c*. Thus, in that case, not only is the extended side **18***b* longer than the shorter side **18***a*, it is also at a higher elevation. Water sculpture **10***c* allows spilling white water **30** to ventilate off the side **20** as run-off water **32**, again avoiding supercritical flow submersion.

Example 4

Simulated Tunnel Wave

One of the most desirable and aesthetically pleasing wave shapes is the tunnel wave. In order to simulate a tunnel wave, a portion of the flow surface is shaped so as to form a generally concave curvature. FIGS. **5** and **6** show two different embodiments of a flow surface particularly adapted to create a tunnel wave. FIG. **5** shows a flow surface with horizontal curvature only (ie. curvature only about a horizontal axis). FIG. **6** shows a flow surface with both hori-

zontal and vertical curvature. These curvatures can be, but do not have to be, circular. Rather, they can be complex, changing curves, such as, an ellipse, parabola, hyperbola, or spiral, as desired.

In FIG. 5, the flow surface **14***d* exceeds the vertical at transition point **34** and curls back onto itself. The velocity head of the supercritical flow **24** is significantly higher than the highest vertical point of downstream edge or ridge line **18**. Supercritical flow **24** moves in a conforming flow upward over the flow surface **14***d* to form an inclined body of water in the shape of a tunnel wave **36**. The slope of flow surface **14***d* gradually increases from zero to about negative ten degrees in the figure shown. However, the flow surface can also be made to curl substantially beyond the ninety degree transition point **34**, such that the flow surface itself forms a substantial portion of a cylinder. Such an embodiment is shown in FIGS. **11** and **12**, which will be further described later.

FIG. **6** shows a second embodiment of a tunnel wave water sculpture **10***e*. In addition to producing the desired tunnel wave, the water sculpture **10***e* can also produce unbroken waves and spilling waves, thereby producing an overall effect of a combination of waves. FIG. **6**A shows a basic preferred shape for a flow surface **14***e* for allowing a supercritically separating flow to form a tube or tunnel that opens onto an unbroken shoulder. A unique characteristic of this basic shape is its ability to enable the separating stream tunnel to form over a wide range of flow velocities and thicknesses and over a flow surface that is not necessarily required to curve past vertical. The basic shape shown in the perspective view of FIG. **6B** generally includes a shoulder region **38**, an elbow region **40**, a pit region **42** and a tail region **44** which, as subsequently described, cooperate to form the tunnel wave as shown.

Referring now to the topographic contour shown in FIG. **6B**, preferred elevations and flow regions are identified. Shoulder region **38** is similar in configuration to previously described flow surface shapes for unbroken wave faces (FIGS. **1** and **2**). In transitioning to elbow region **40** flow surface **14e** begins bending or sweeping in smooth curvilinear fashion in a downstream direction. Concurrent with this downstream sweep, flow surface **14***e* begins to increase in steepness with downstream ridge line **18** simultaneously increasing in elevation. At its maximum angle of sweep, elbow region **40** transitions to a pit region **42** whereupon flow surface **14***e* continues to increase to its maximum steepness and concavity and ridge line **18** increases to its maximum elevation. Swale **46** serves to ventilate subcritical spilling white water during start-up, as well as the white water that appears when the lip of the tunnel reconnects. Swale **46** is formed by a smooth sculpted depression in sub-equidyne area **48** of the tail region **44**.

FIG. **6C** illustrates streamline characteristics of water flow from a suitable flow source **22** (e.g., pump, fast moving stream or elevated dam/reservoir) providing a supercritical sheet flow of water **24** in an initial flow direction **26**. The hydraulic characteristics of the flow and its synergistic interaction with the flow surface **14***e* is best described by reference to each respective sub-region.

In shoulder region **38**, the sole source of outside pressure is due to gravity. The uniform rate of surface incline results in flow **24** taking a predominantly two dimensional straight trajectory up flow surface **14***e* and over downstream ridge line **18** as indicated by a streamline **50***a*.

In the elbow region **40**, a backwards or downstream sweep in the inclined portion of surface **14***e* creates a low pressure area towards the backswept side. As flow **24** rises in elevation upon elbow region **40**, flow **24** begins to turn toward the area of lower pressure as indicated by the solid streamline **50***b*. Now flow **24** is no longer following a two dimensional streamline. Rather, the streamline path **50***b* moves in three dimensions due to the cross-stream pressure gradient. The trajectory of flow **24** as indicated by the solid streamline **50***b* is spirally shaped. If hypothetically extended (indicated by continued dashed line), the last half of this spiral would be directed downslope and conforming to the backswept side of the flow surface **14***e*.

In pit region **42**, the flow **24** again rises in elevation and then turns toward the area of lower pressure as indicated by solid streamline **50***c*. The trajectory of flow **50***c* is parabolically inclined and, if hypothetically extended (indicated by continued dashed line), would separate from flow surface **14***e* and would arc downward until reconnecting in the pit area **44**. The swale **46** formed in area **48** combined with an increasing steepness of flow surface **14***e* results in a parabolic trajectory that moves up straighter and more vertically, as illustrated by streamline **50***c*. This leads to flow separation resulting in the desired stationary tunnel opening to an unbroken shoulder. As supercritical flow **24** separates from flow surface **14***e*, its new direction of flow, as indicated by the dashed portion of streamline **50***c*, is generally transverse to the original direction of flow **26**. When streamline **50***c* reattaches to the flow **26**, white water **30** appears and forms a tail race **52** as guided by tail region **44**.

A prerequisite to tunnel wave formation is that supercritical flow **24** must have at least sufficient velocity to clear downstream ridge line **18** on shoulder area **38**.

Further increases in the velocity of supercritical flow **24** will result in an increase in tunnel diameter, i.e., an increase in apparent wave size.

At least three characteristics of the flow surface influence the overall appearance of the tunnel wave and each of them interacts with the other: (1) its shape; (2) its attitude or horizontal angle with respect to the direction of water flow; and (3) its inclination or vertical angle with respect to the direction of water flow.

The flow surface of the tunnel wave water sculpture **10***e* of FIGS. **6A–6B** preferably has a shape having concave curvature both vertically and horizontally as indicated. The shape of the vertical curvature can be a simple arc or circle or, more preferably, an arc of a more complex changing curve such as an ellipse, parabola, helix, or spiral. If a changing curve is selected, it preferably changes from the opening curve at the leading edge through a transition point to a closing curve at the trailing edge such that the ascending water encounters a decreasing radius as it ascends up the flow surface. At a transition point the flow surface begins to curve past the vertical to about negative 10 to 30 degrees. The shape of the horizontal curvature can be a simple arc or circle, or, more preferably, a portion of a more complex changing curve such as an ellipse, parabola, helix, or spiral.

The horizontal attitude of the flow surface with respect to the direction of water flow can vary within certain limits so as to facilitate the formation of the tunnel wave. Since the front surface of the concave curvature has varying degrees along its horizontal axis for purposes of orientation an extension of upstream edge is used to indicate varying horizontal attitudes of the front face therefrom. Accordingly, upstream edge varies from substantially perpendicular to the direction of water flow to a preferred angle of approximately 35–45 degrees, as shown.

Two additional factors are particularly important with respect to the inclination: (1) the change in angle of incline relative to the depth of water is preferably sufficiently

gradual to avoid separation or deflection of streamlines; and (2) the angle of release (the line tangent to the front face of the downstream edge when compared to the vertical) is preferably beyond vertical as shown (although this is not necessary). Amounts of incline beyond vertical may vary, as desired; however, a preferred amount is about 10 degrees.

FIGS. 7A, 7B and 7C illustrate yet another unique feature of a flow surface **14***e* as configured in FIG. **6**. In this embodiment, the wave shape can be formed by way of a progressive increase of the velocity of the water flow so as to cause transformation of supercritical water flow **24** that originates from a water source (not shown) in direction **26** to a stationary white water bore along the entire upper ridge of the flow surface (as illustrated in FIG. 7*a*); to a stationary spilling wave with an unbroken shoulder (as illustrated in FIG. 7*b*); to a stationary tunnel wave with unbroken shoulder (as illustrated in FIG. 7*c*). If desired, this progressive water sculpture may be formed using a suitable flow surface to create a dynamic "flow transformation process" culminating in the formation of a tunnel wave.

Example 5

Half-Pipe Flow Configurations

To this point, the sheet flow upon the flow surface has been described as issuing at either an upward incline or horizontally. However, water flowing upon downhill ramps may also have advantages in connection with simulated wave formation. When the source for such flow is from a pump or darn/reservoir with associated aperture, e.g., nozzle, there is significant likelihood that oblique waves (i.e., non-coherent streamlines) will form at an angle to the flow as a result of boundary layer disturbances associated with the aperture enclosure. Oblique waves may grow and lead to choking of an entire flow. The use of downhill ramps can help solve or mitigate this problem by encouraging smooth sheeting flow. Further, downhill ramps add new possibilities for the creation of water sculptures with enhanced visual, aural or aesthetic appeal.

FIG. **8** shows a water sculpture **10***f* having an angular extension of inclined flow surface **14***f* creating a downhill ramp **62** upon which flow source **22** initially issues supercritical flow **24**. This extension or downhill ramp **62** can also be characterized as an extension of the sub-equidyne area of the flow surface **14***f* and creates a downhill ramp **62** of sufficient decline to inhibit oblique wave formation (i.e., oblique waves are swept downstream). The declined ramp **62** then transitions to an extended intermediate area **48** before ascending up the inclined ramp and over the downstream edge or ridge line **18**.

The various sections of the flow surface **14***f* of FIG. **8** need not be so well-defined. Rather, the surfaces can be gradually curved so as to form a continuous curving surface between the upstream edge **16** and the downstream edge **18**. In a particularly preferred configuration, these surfaces can form a half-pipe flow surface **14***g*, as shown in FIG. **9**. The half-pipe water sculpture **10***g* consists of a source pool **66** that supplies a flow of water that turns to a supercritical flow of water **24** shortly after overflowing the upstream edge **16**. The water then flows in a direction **26** across the half pipe and over the downstream ridge or edge **18**, and into a receiving pool **68**. Numerous other configurations involving downhill ramps, horizontal surfaces and inclined surfaces are also possible by varying the curvature and choice of the flow surface **14***g*.

Example 6

Tunnel Wave Awning

The ability to create stable simulated waves as described above leads to several additional unique possibilities in the field of water sculpture. One particularly exciting possibility is the ability to reproduce the experience of actually being inside a tunnel wave. The sight, sound and sensation of walking through a tunnel wave is a thrilling experience and has heretofore only been available to relatively few people in the world capable of surfing in a naturally occurring tunnel wave or tube. Advantageously, the subject invention allows this prized experience to be enjoyed by virtually anyone who can walk or otherwise traverse down a walkway. The particular examples discussed herein should not be construed as limiting the present invention in any way. Rather, these teachings apply generally to any application which can take advantage of the aesthetic appeal of simulated wave shapes.

FIG. **10**A shows a tunnel wave water sculpture **10***h* forming an entranceway or awning for a building. A giant tunnel wave **36***a* is formed at the entrance area **70** of a building **72**, as shown. A walkway **74** is surrounded by a pool of water **80** and extends through the tunnel wave **36***a* in order to allow a person **76***a* to walk through the tunnel wave **36***a* to enter or exit the building **72**. The tunnel wave thereby forms a unique water "awning" for the building. Other wave shapes may also be formed adjacent other portions of the walkway **74**, as desired. For instance, to the left of person **76***b* another tunnel wave **36***b* is formed that does not extend over the walkway **74**. Several other wave shapes could also be formed to surround the walkway and/or the building, thereby enhancing the aesthetic appeal of the overall structure. The water sculpture **10***h* may be appropriately contoured in accordance with any variety of flow surfaces described above to form a variety of desired wave shapes, such as non-broken waves, white water bores, spilling waves, tunnel waves and/or combination waves. If desired, an optional waterfall **75** or other water effect may be provided between the interface of the tunnel wave and the building **72** in order to mask undesirable dry or exposed areas and/or to create dramatic whitewater effects, expanding or enhancing the visual, aural or aesthetic appeal of the water sculpture **10***h* and the associated building **72**.

FIG. **10**B shows the tunnel wave awning water sculpture of FIG. **10**A in cross-section taken along section lines **10**B—**10**B. One or more flow sources **22** are located underneath the walkway **74** submerged within the pool of water **80**. The water from the flow sources **22***a–i* flows through a nozzle **23** onto an inclined flow surface **14***g* that is contoured and shaped as shown. The flow surface may or may not curve past vertical at this point, depending the desired effect and the upstream contour of the flow surface **14***h*. Water forming the tunnel wave **36***a* flows over the walkway, as shown, and returns to the pool of water **80** where flow source **22** is located. Therefore, water recycling is advantageously employed. If desired, an optional shield **77** may be provided inside the free falling tunnel wave **36***a* and extending outward from the building entranceway **70** to protect persons **76***a,b* on the walkway **74** from getting wet.

Theoretically, no pool or water reservoir is required for the water sculpture since a flow from a suitable flow source is all that is required. However, where water recycling is preferred, low channel walls can be constructed to retain the flowing water with a lower collection pool recycling pump and appropriate conduit connected back to the upstream flow source. The area of channel containment need only be large enough to form the tunnel wave since most of the returning water of the tunnel wave will remain more or less stationary within the containment structure. Thus, such a structure can be constructed even in a limited amount of space.

FIG. **10**C shows a schematic plan view of the tunnel wave awning water sculpture of FIGS. **10**A–B, illustrating a